

# Prospects to search for light feebly-interacting scalar particles at MATHUSLA, CODEX-b, FASER, ANUBIS

**FIPs 2020 CERN Virtual Workshop**

**4 September 2020**

**David Curtin**



UNIVERSITY OF  
TORONTO

# Introduction

At this workshop, motivation for LLPs and FIPs needs no introduction.

“Scalar FIPS”  $\leftrightarrow$  Higgs Portal?  $\lambda_{HS} S^2 |H|^2$  or  $ch\psi\bar{\psi}$ ?

or only theories that contain SM+S simplified model?  $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - (\mu S + \lambda S^2) |H|^2$

or only scalar LLPs?

The *spin* of the LLP is generally not very important for experimental searches. Does not uniquely determine production/decay mode and lifetime (might bias our expectations a bit).

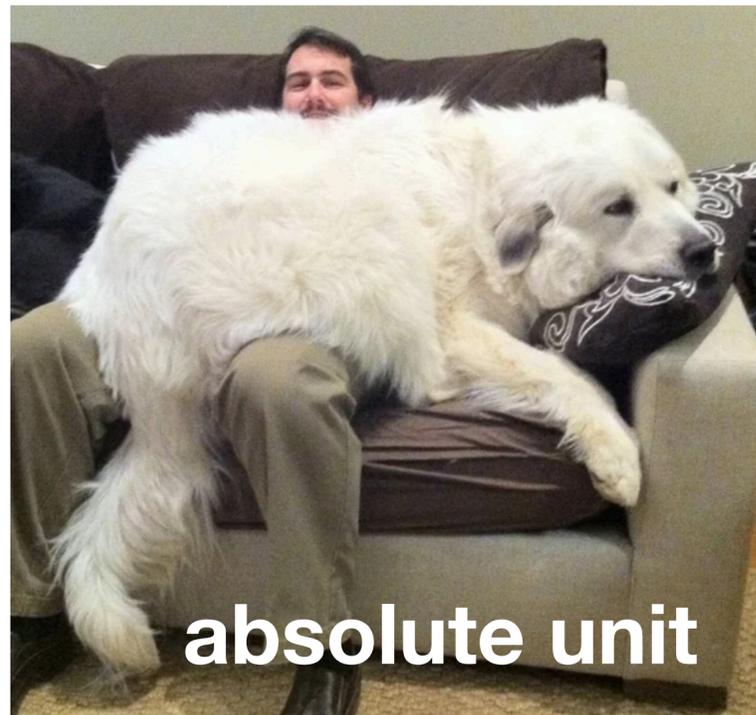
**I will focus on  $h \rightarrow XX$  LLP production (“higgs portal”) and SM + S simplified model.**

Not the same, but important overlaps:

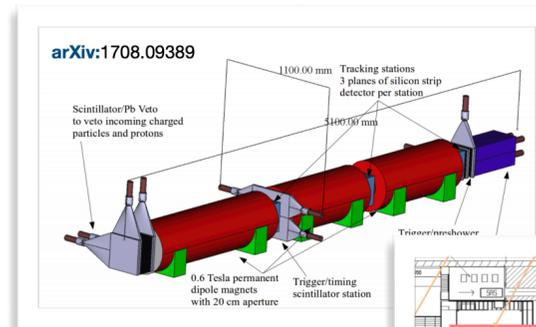
SM+S has  $h \rightarrow LLP$  and  $B \rightarrow LLP$  with particular mass-lifetime relation, but  $h \rightarrow LLP$  could also produce e.g. scalar dark glueballs with lifetime  $\sim$  independent of  $\text{Br}(h \rightarrow LLP)$ .

The details of the LLP model influence how you map it to e.g. astro constraints  
(c.f. shameless plug for *Mirror Stars*, 1909.04072, 1909.04071 DC, Jack Setford)

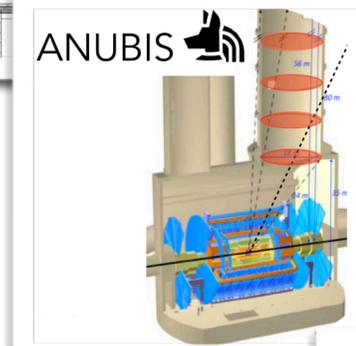
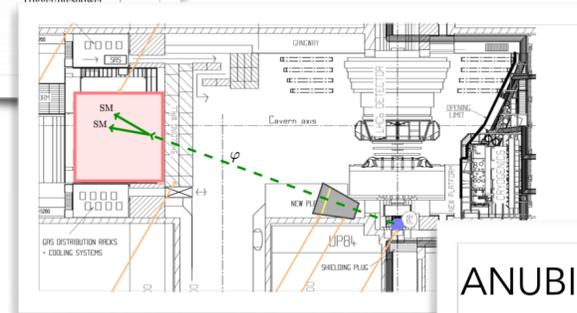
# External LLP detectors for the (HL-) LHC



**FASER**

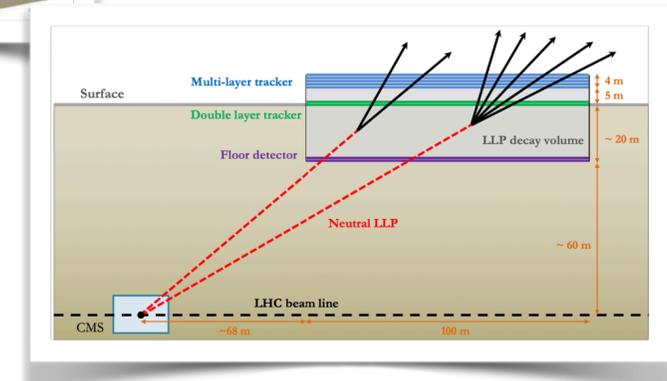


**CODEX**



**ANUBIS**

**MATHUSLA**



I will introduce the smol-er three, then discuss recent updates for MATHUSLA (arxiv) and compare/discuss LLP sensitivities.

# FASER

- **FASER experiment being built with significant speed**

▶ **~4 years from proposal to expected first data taking**

- **Well integrated into new COVID-19 adjusted LHC schedule**

▶ **Expected full underground installation at T112 by end of year (2020)**

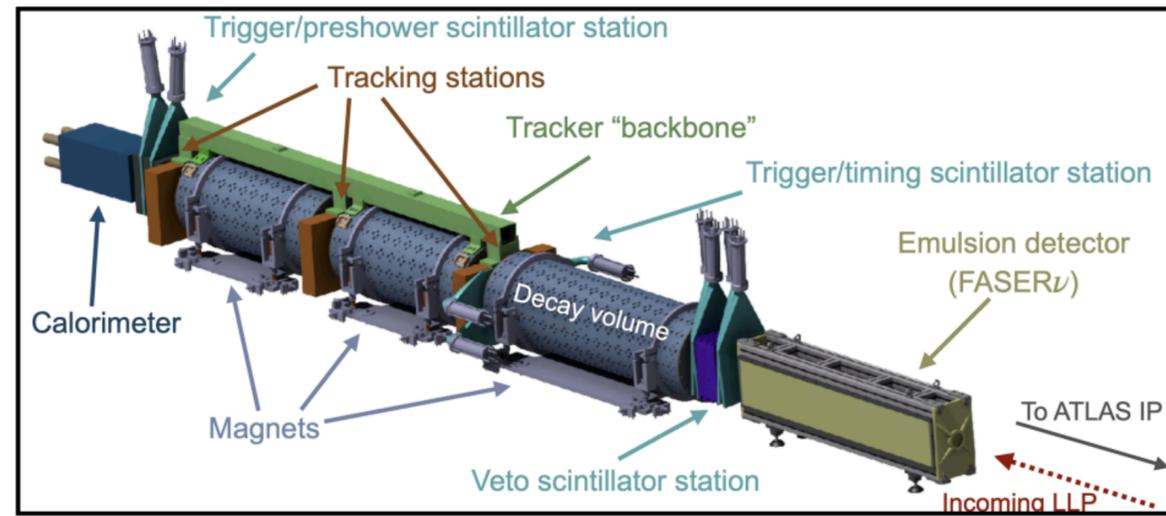
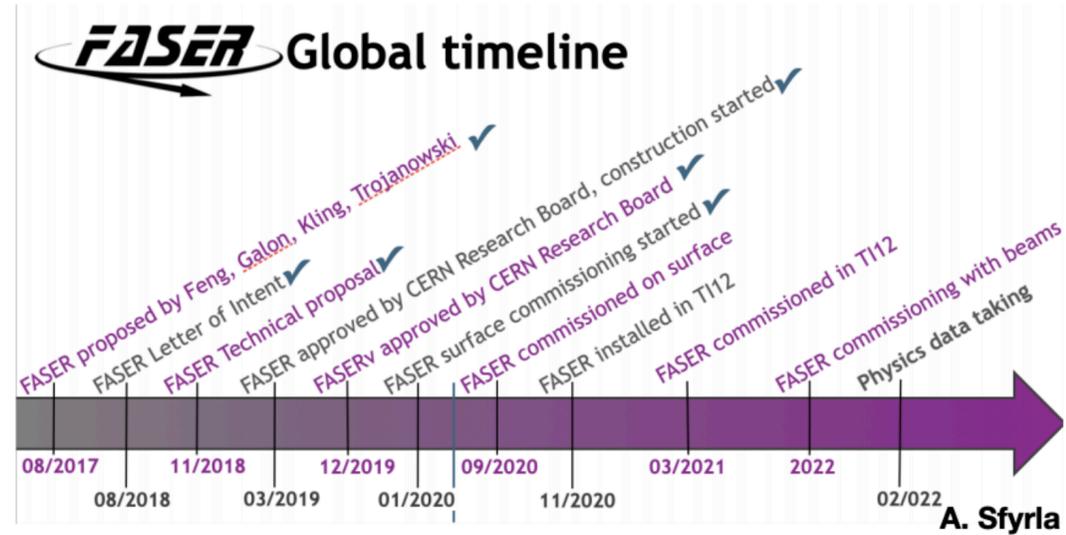
★ Pending on schedule for LHC Sector 81 cool down and magnet training

- **Dedicated neutrino detector FASER $\nu$  to be installed in front of FASER before Run-3**

▶ **2001.03073, 1908.02310**

- **Enlarged FASER( $\nu$ )2 detector proposed for Phase-2**

▶ **Snowmass LOI, 1811.12522**



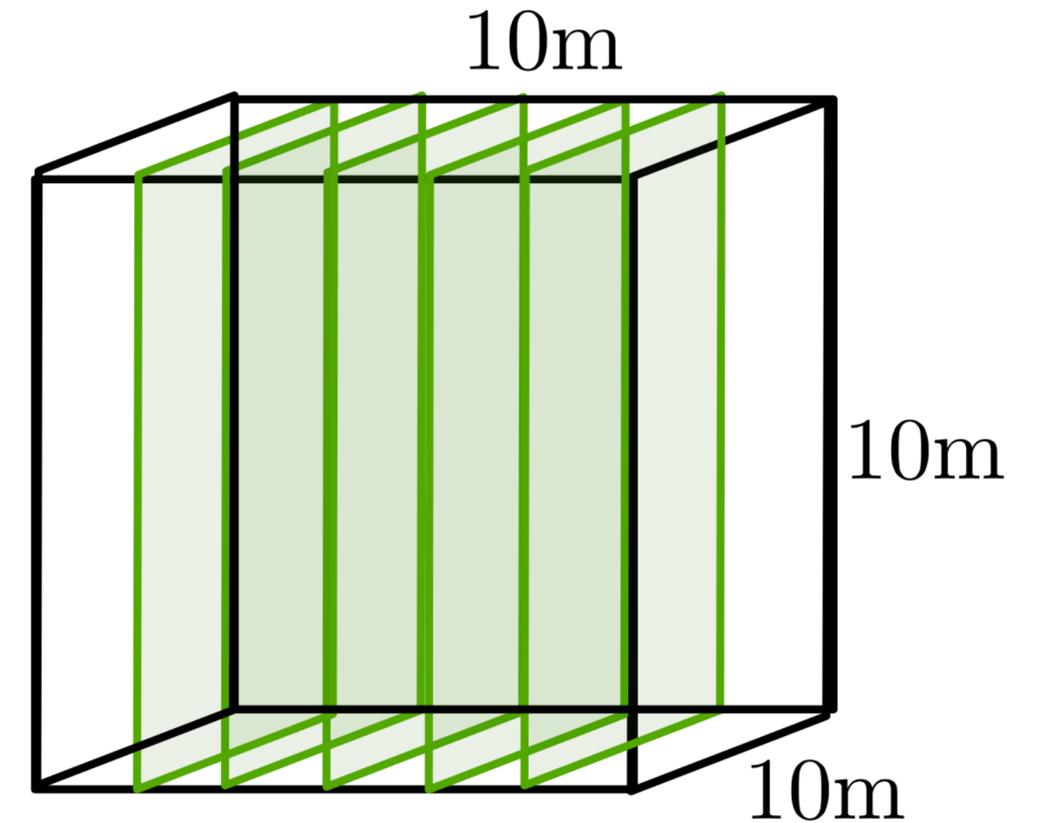
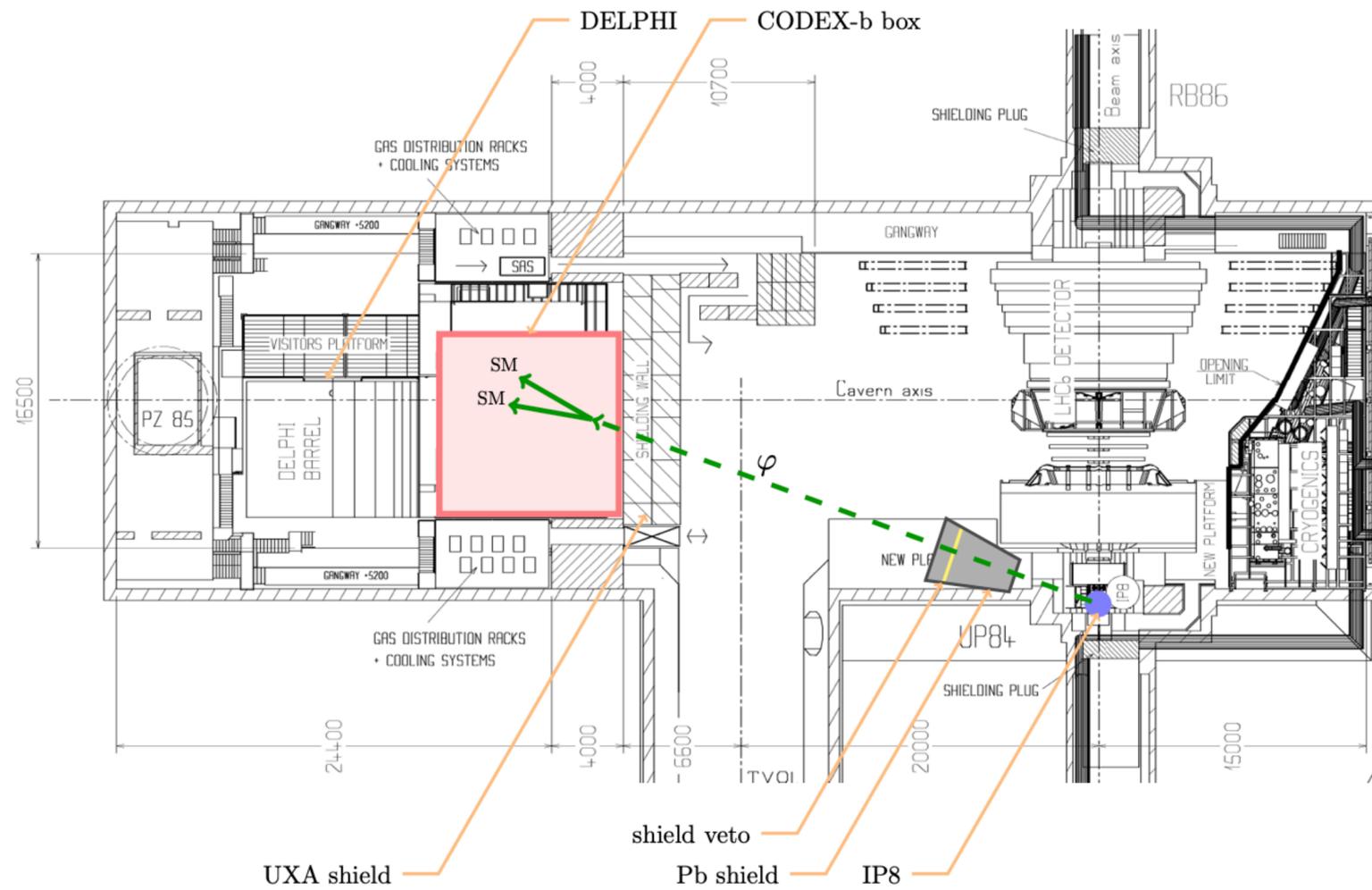
**FASER** was nicely introduced by Jakob Salfeld-Nebgen's talk, e.g. this slide.

*Upshot: a relatively small meter-scale particle-telescope in the LHC tunnel to use 'longitudinal enhancement' of production xsecs, turning the LHC into an intensity frontier experiment for low-mass LLPs.*

*Very on-shell!  
Exciting!*



# CODEx-b: a shielded tracker box near LHCb



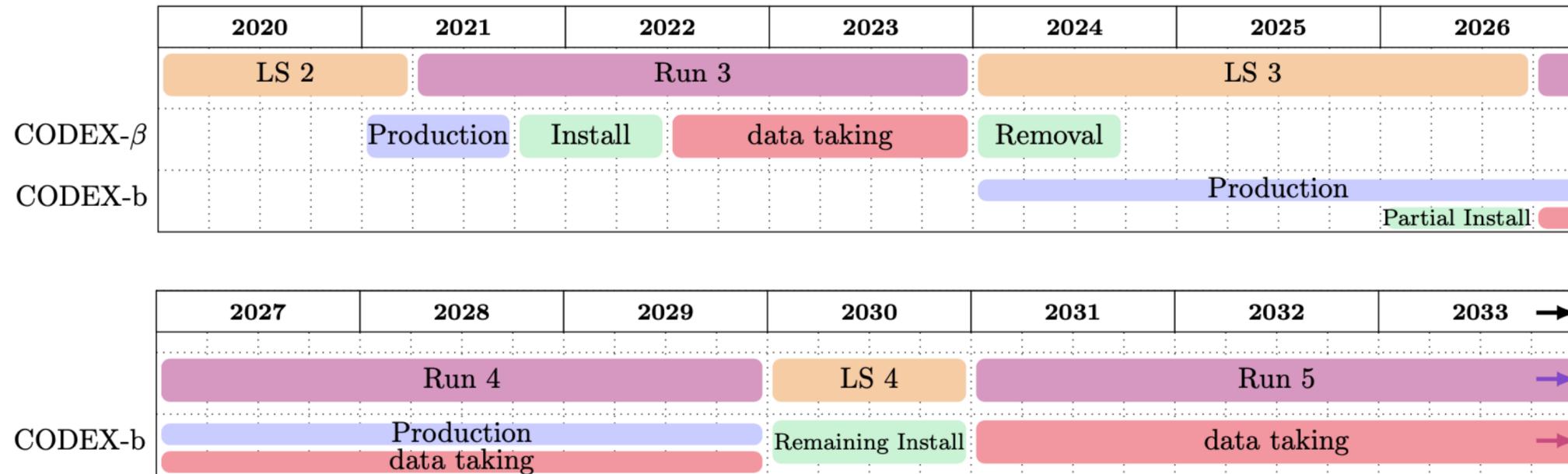
*Upshot: a modest-size **transverse** LLP detector that can be integrated with LHCb*

Expression of Interest: 1911.00481

# CODEX-b: Timeline

Silde by Philip Ilten

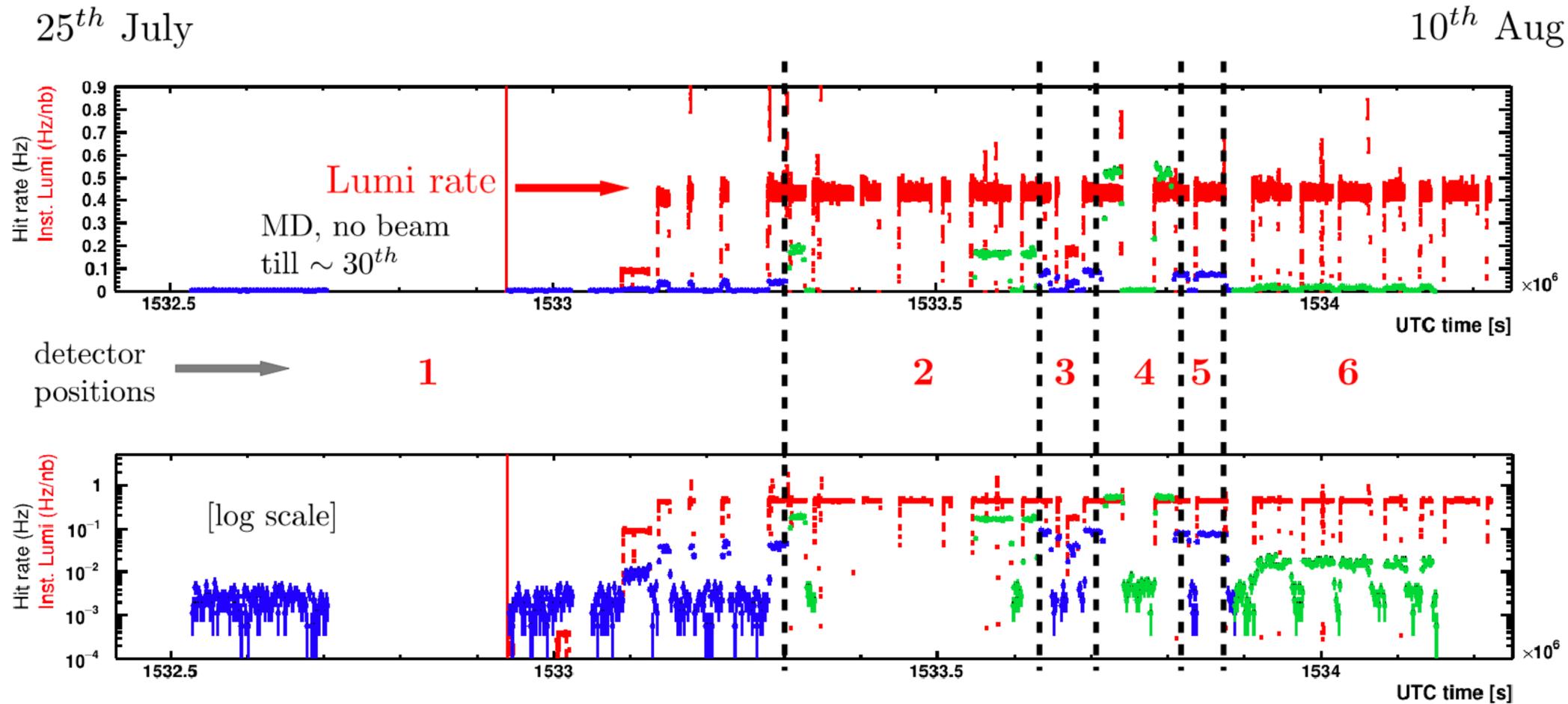
pre-COVID timeline



- significant progress has been made
- priority is finalising CODEX- $\beta$  design and plans
- Birmingham (James Glover) working on technical drawings
- more detailed design informed from CODEX- $\beta$

# CODEX-b: Backgrounds

Silde by Philip Iiten



- 0.2 Hz hit rate at point 2 indicates GEANT4 prediction of 10 Hz is conservative

# CODEX-b: Demonstrator Unit

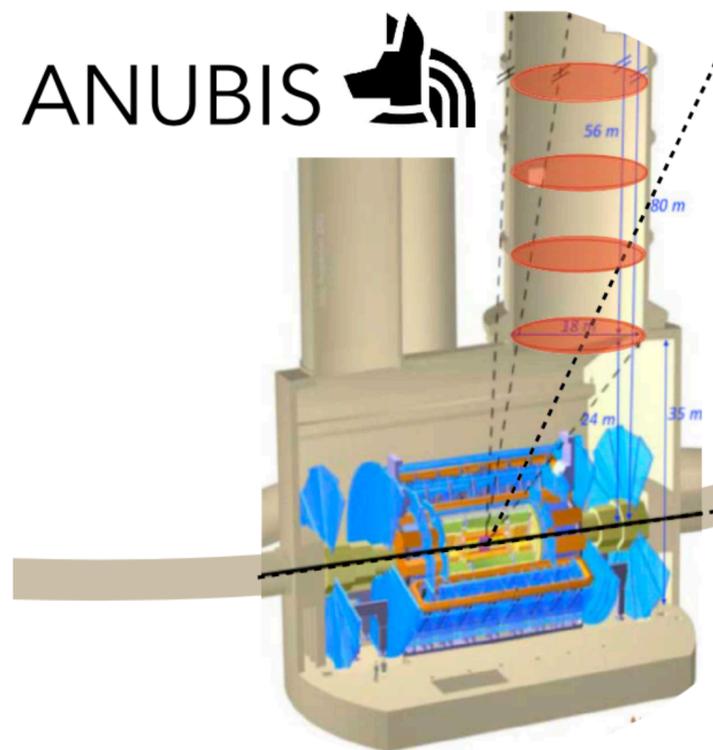
Silde by Philip Ilten

## CODEX- $\beta$

- $2 \times 2 \times 2 \text{ m}^3$  with central layer, each layer with triplet of RPCs
  - each layer made of  $2 \times 1 \text{ m}^2$  RPC block, 42 such layers
  - expected hardware cost of 150k EUR
- ① *Demonstrate the ability to detect and reconstruct charged particles which penetrate into the DELPHI cavern as well as the decay products of neutral particles decaying within the DELPHI cavern.*
  - ② *Detect and reconstruct a reasonable rate of neutral particles decaying inside the hermetic detector volume.*
  - ③ *Show that CODEX-b can be integrated into the LHCb DAQ and demonstrate an ability to give a trigger to LHCb to retain an event that looks interesting in CODEX-b.*

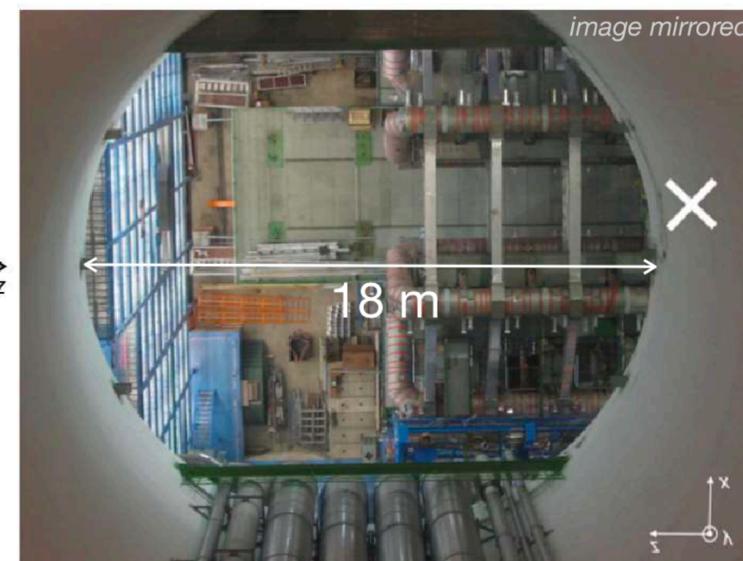
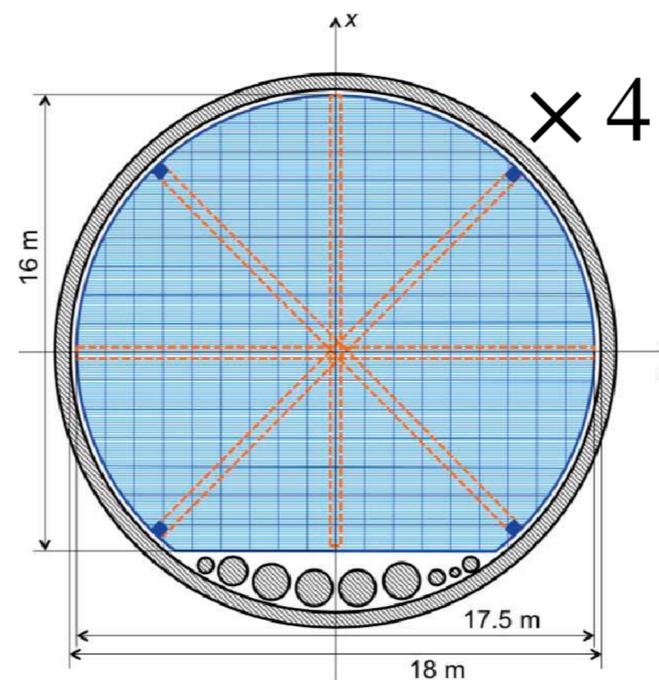
# ANUBIS: an ambitious chandelier in the ATLAS shaft

Silde by Oleg Brandt



We propose to instrument the ATLAS service shaft

Bauer, OB, Lee, Ohm 1909.13022



Current proposal:  
Four evenly spaced tracking stations with a cross-sectional area of 230 m<sup>2</sup> each

# ANUBIS: backgrounds



It should be possible to dramatically reduce backgrounds.  
The ATLAS detector serves:

- as a passive shield:  
calorimeters account for  $\sim 10$  nuclear interaction lengths  $\lambda_I$
- as an *active veto*:  
high- $p_T$  neutral particles ( $n, K_L$ ) typically come with energetic jets

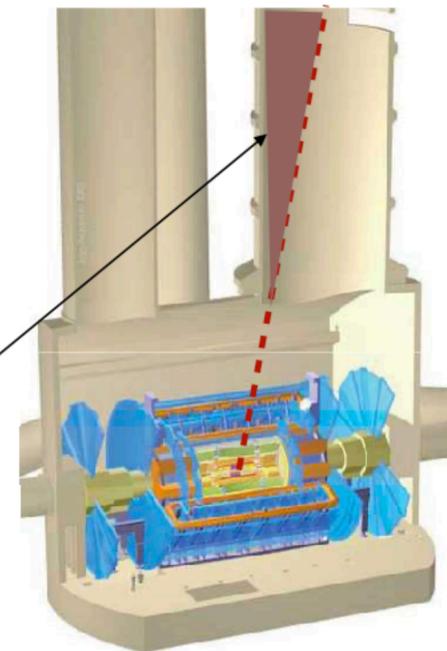
Almost background-free by requiring isolation in  $\Delta R(DV, x)$

- from inner detector tracks
- from calorimeter jets
- from muon spectrometer tracks

Achieve this by *ANUBIS triggering the readout of ATLAS*

Additional shielding by rock between the interaction point and some regions of the tracking stations:

-> useful as control region



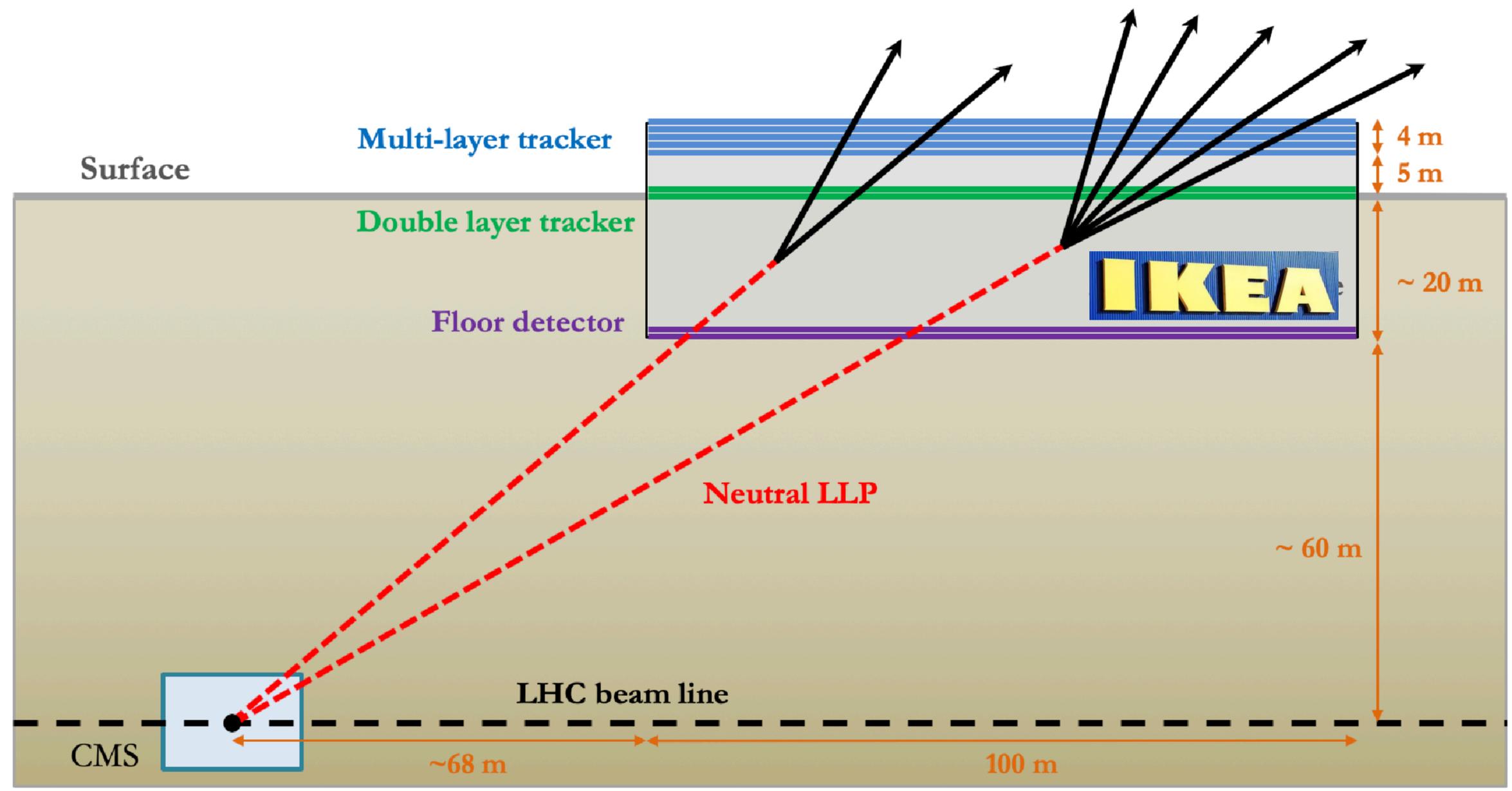
Silde by Oleg Brandt

*Upshot: a possibly very economical, but perhaps “invasive”, approach to instrumenting a large transverse LLP decay volume with trackers.*

*Relies on main detectors for BG veto.*

# MATHUSLA: a big-box store at CERN

Build an IKEA near ATLAS or CMS and put trackers in the ceiling. LLPs that stop to buy furniture will be reconstructed as displaced vertices.



Stringent geometrical + timing LLP reconstruction criteria and ~100m of rock shielding allow for LLP searches in “near-zero background environment”

# MATHUSLA Physics Case + Collaboration

## Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

1806.07396

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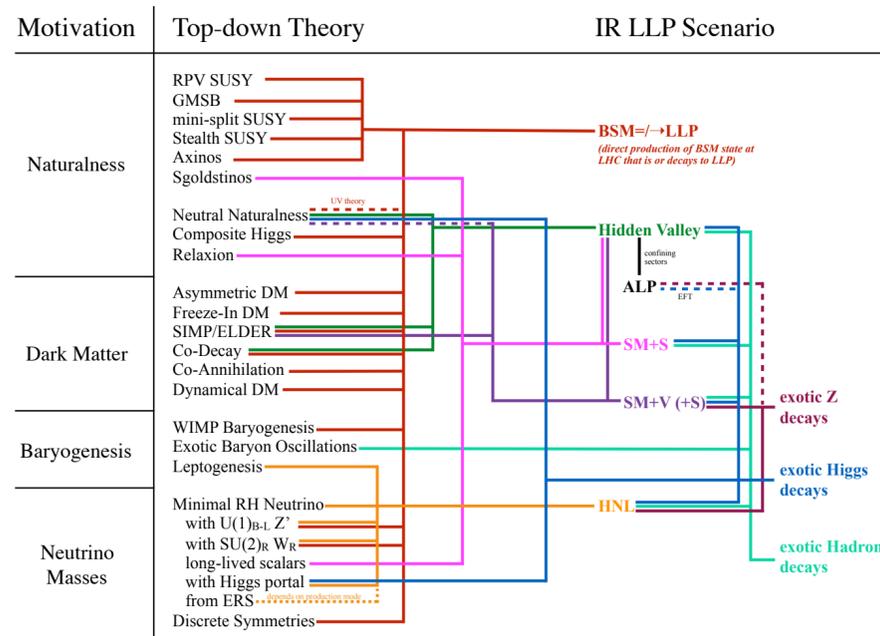
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## A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

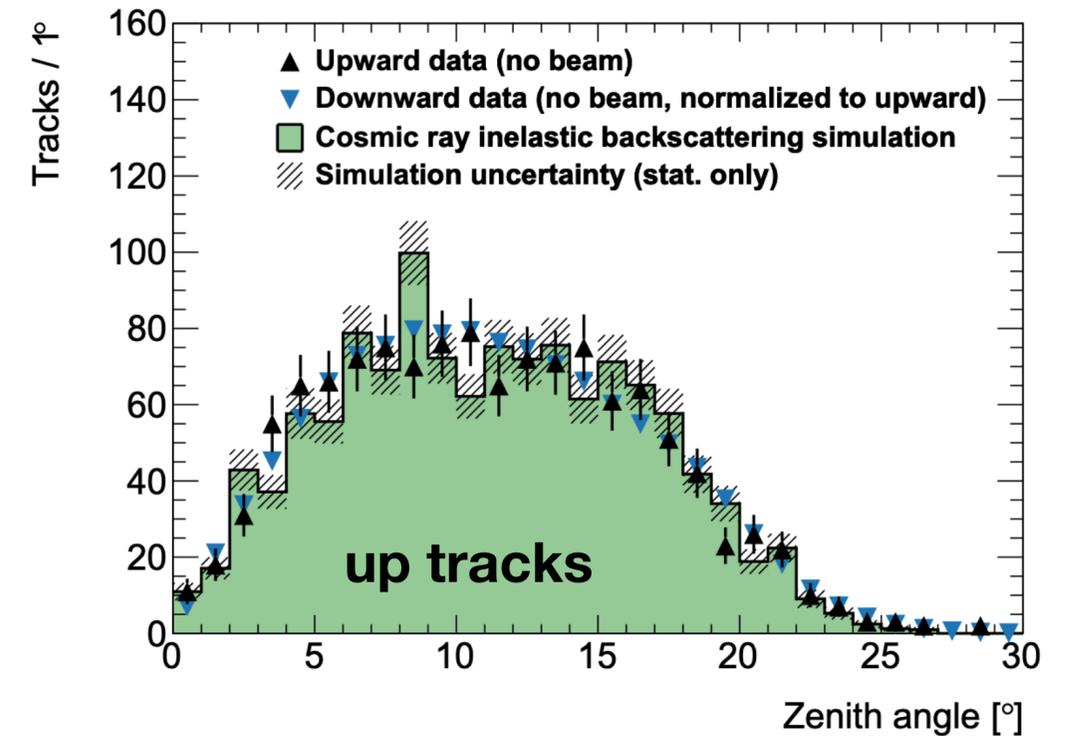
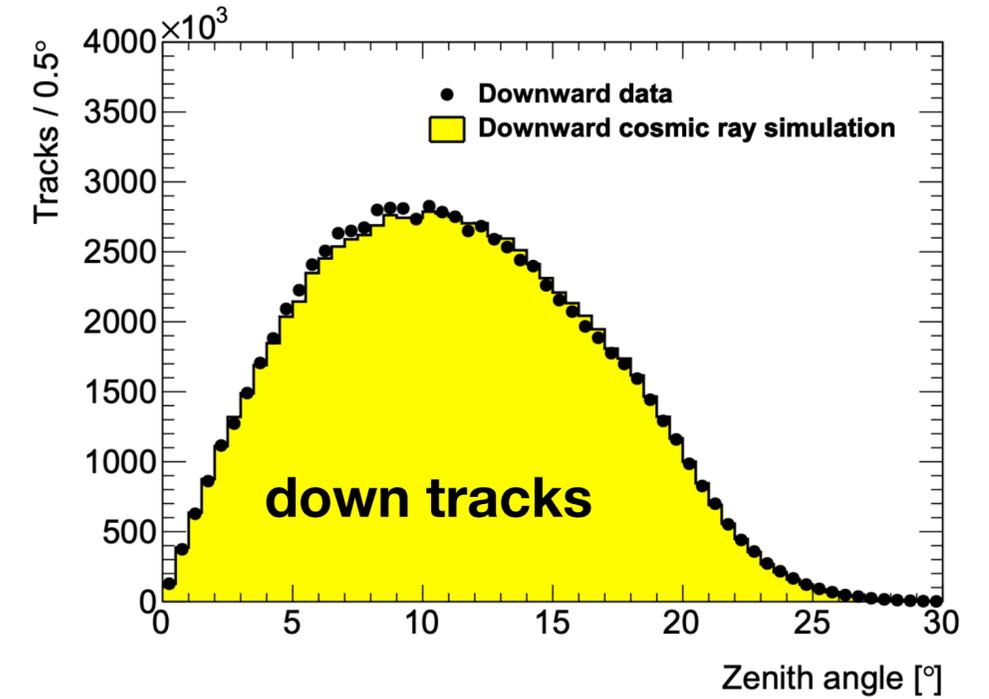
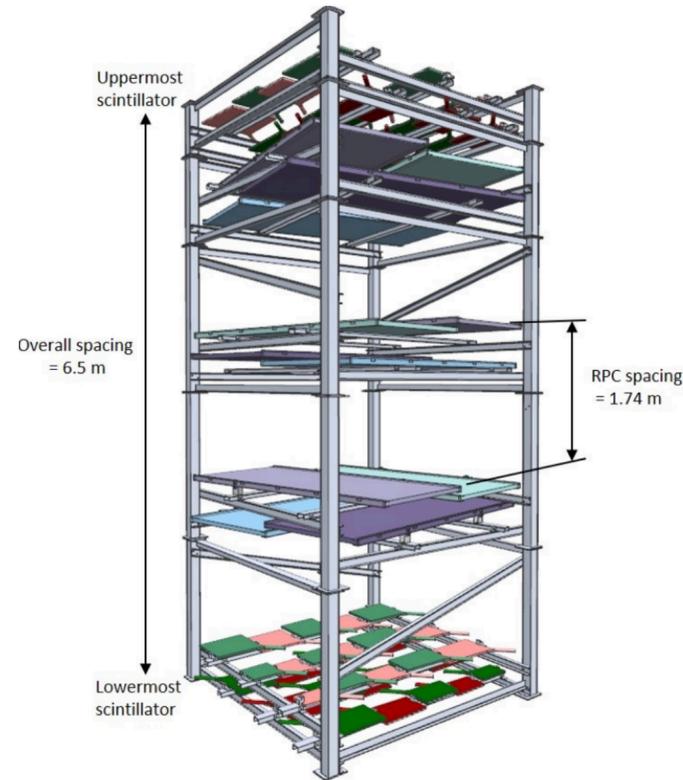
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Emma Torro,<sup>a</sup> Yuhsin Tsai,<sup>u</sup> Juan Carlos Arteaga-Velázquez,<sup>i</sup> Gordon Watts,<sup>a</sup> Charles  
Young,<sup>e</sup> Jose Zurita.<sup>w,ac</sup>



# MATHUSLA Test Stand

Operated above ATLAS in 2018,  
results in 2005.02018



**Downward cosmic rays, upward LHC muons and upward CR backscatter well described by simulations!**

$$R_{\text{up-to-down}} = \frac{(\text{Number of upward tracks})_{\text{data, no beam}}}{(\text{Number of downward tracks})_{\text{data, no beam}}} = (7.0 \pm 0.2) \times 10^{-5}$$

# Recent Updates

Summarizes progress since the LOI:

- Realistic detector geometry: 1/4 the size of MATHUSLA200, same sensitivity
- Updated detector design: scintillators instead of RPCs
- Some more tracking layers to be on the safe side
- Background studies calibrated by test stand data
- Next steps

**An Update to the Letter of Intent for MATHUSLA:  
Search for Long-Lived Particles at the HL-LHC**

**MATHUSLA**

[mathusla-experiment.web.cern.ch](http://mathusla-experiment.web.cern.ch)

*On arXiv today!*

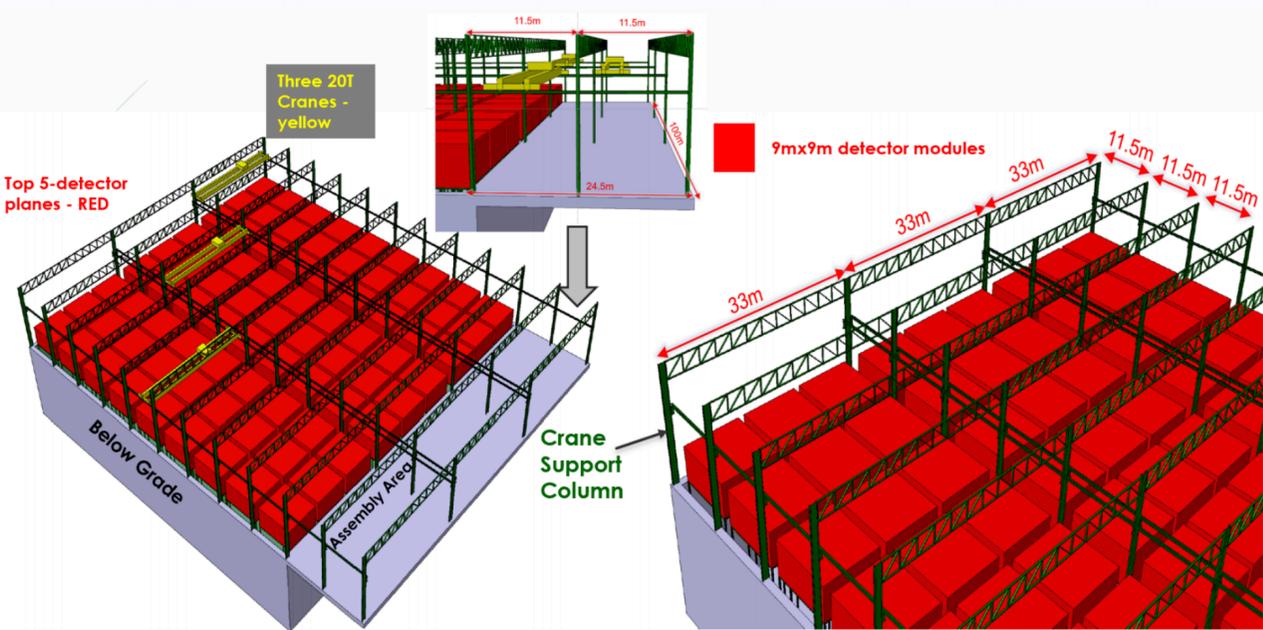
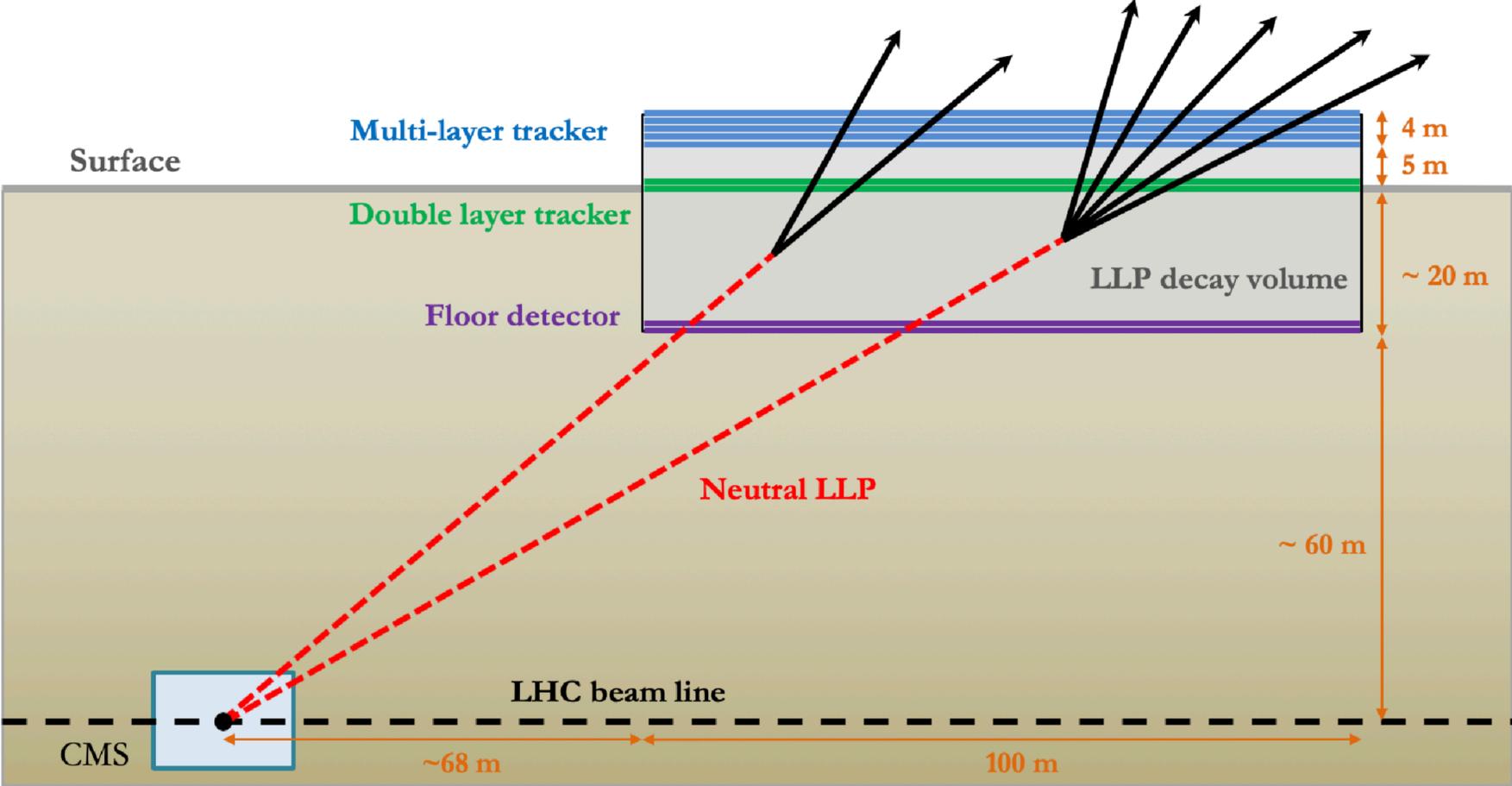
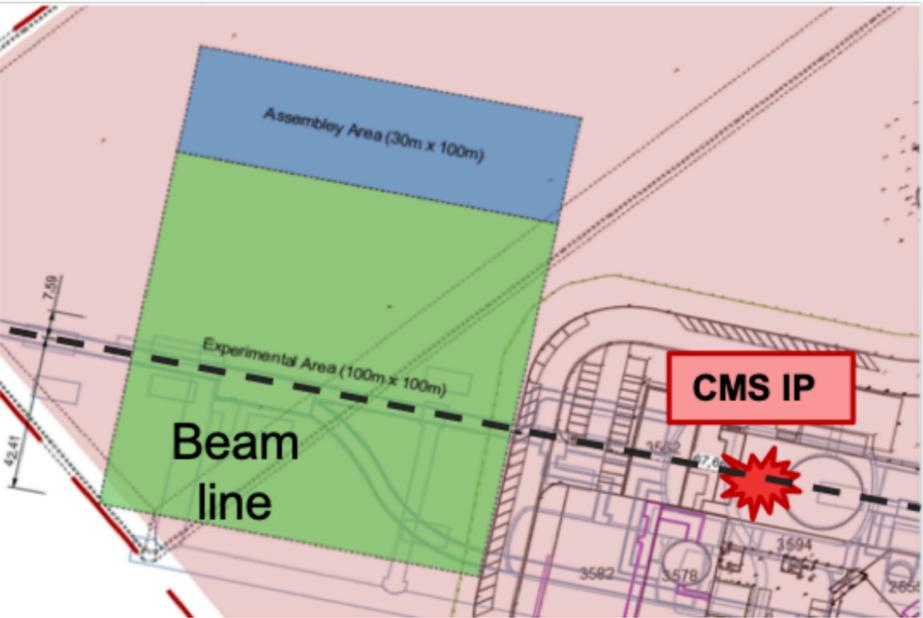
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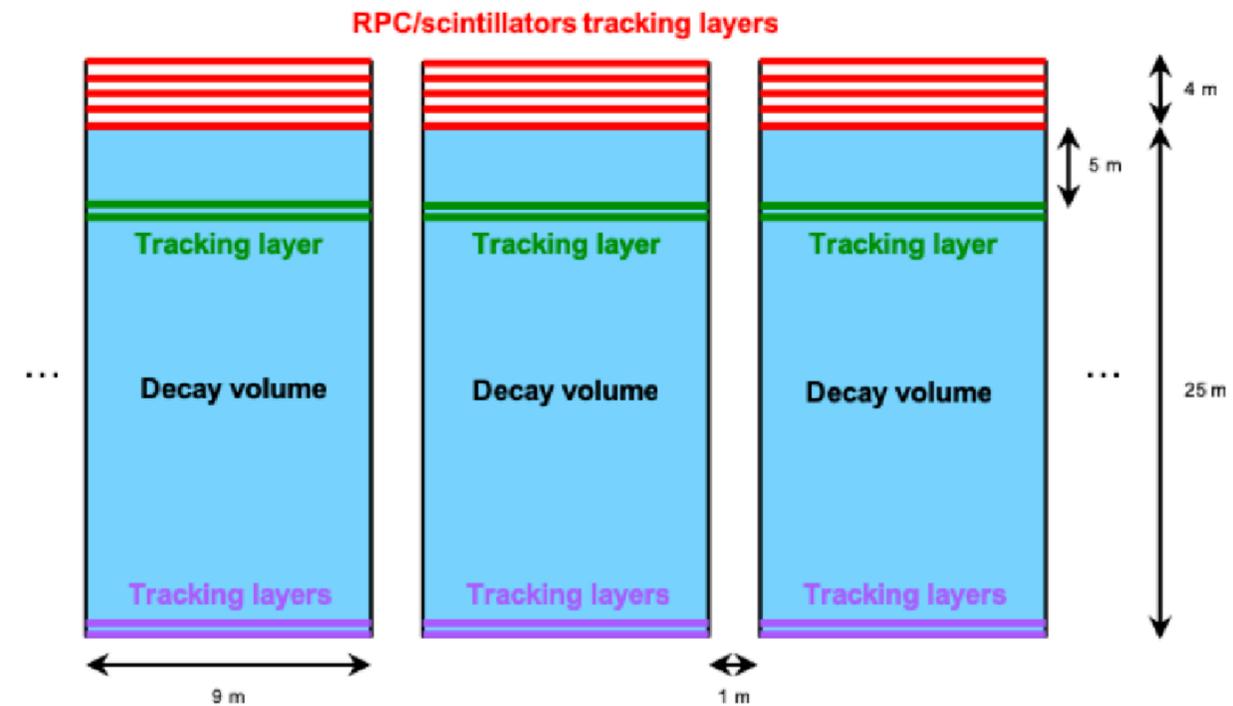
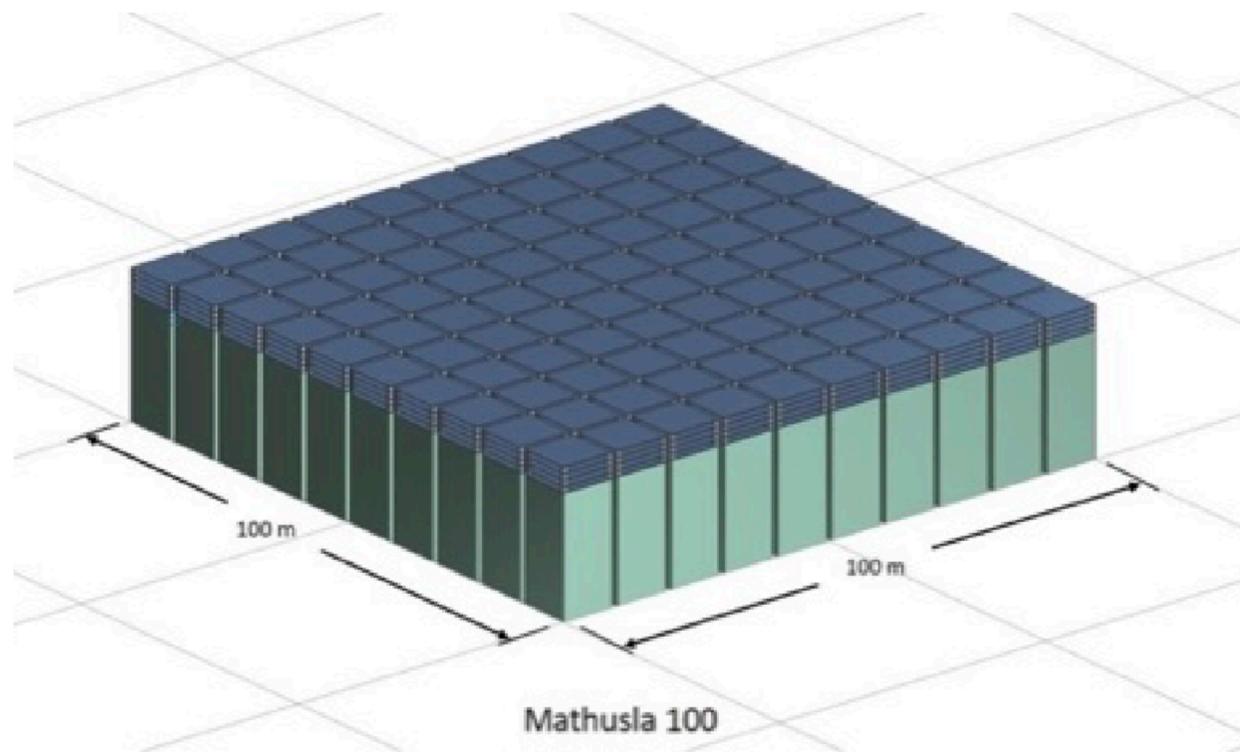
# MATHUSLA @ CMS

CERN Engineers conducted site-specific engineering study to identify location for partially **excavated** decay volume on CERN-owned land, and exploratory design of building structure..



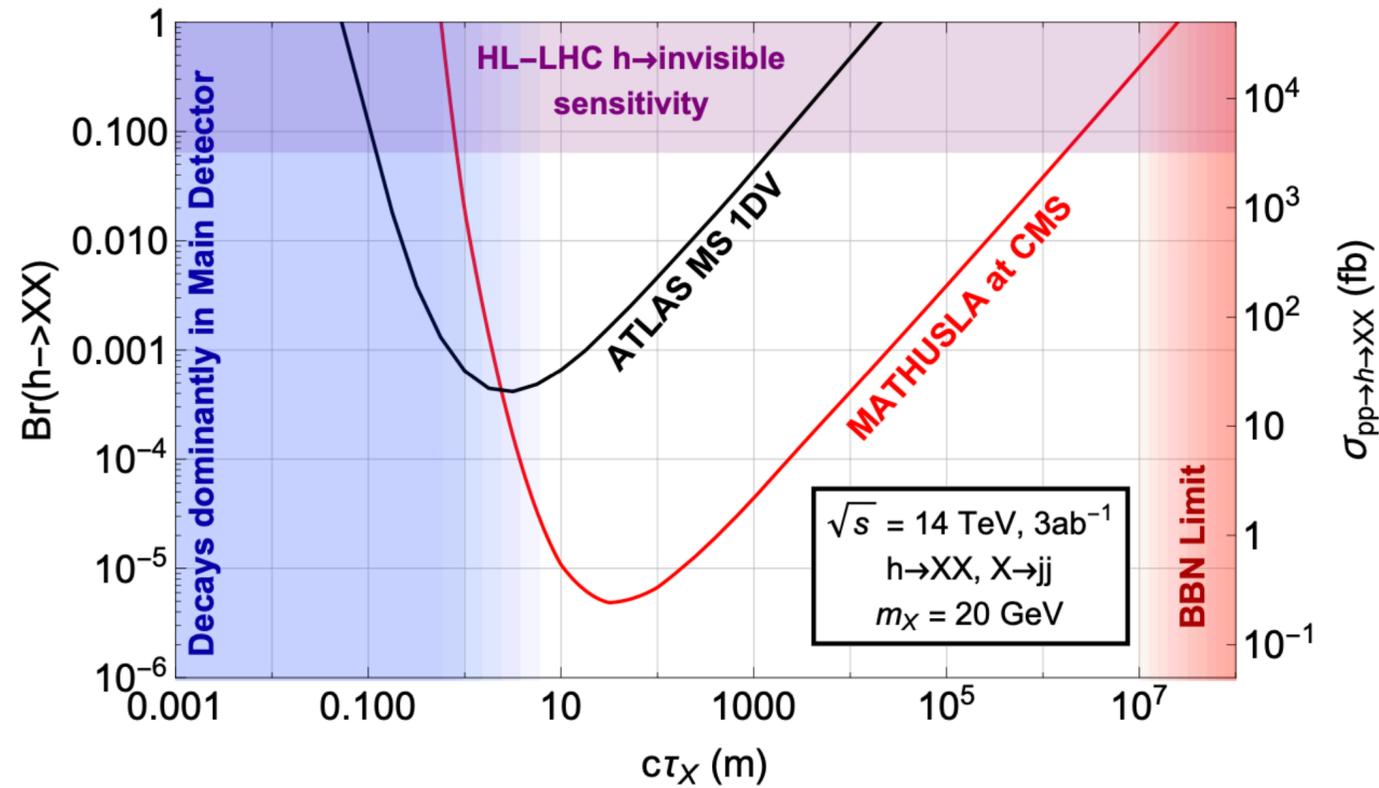
Updated geometry:  
**100m x 100m x 25m decay volume,**  
**displacement from IP is 70m horizontally, 60m vertically**

# Modular Detector Design



Preliminary design: added floor & middle tracking layers. 100 modules, 9m x 9m. Tracker technology is extruded scintillators, bars of length  $\sim 4.5\text{m}$  and width  $\sim 2\text{cm}$  + central wavelength shifting fiber, readout by SiPM.

# LLP Sensitivity: $h \rightarrow$ LLP



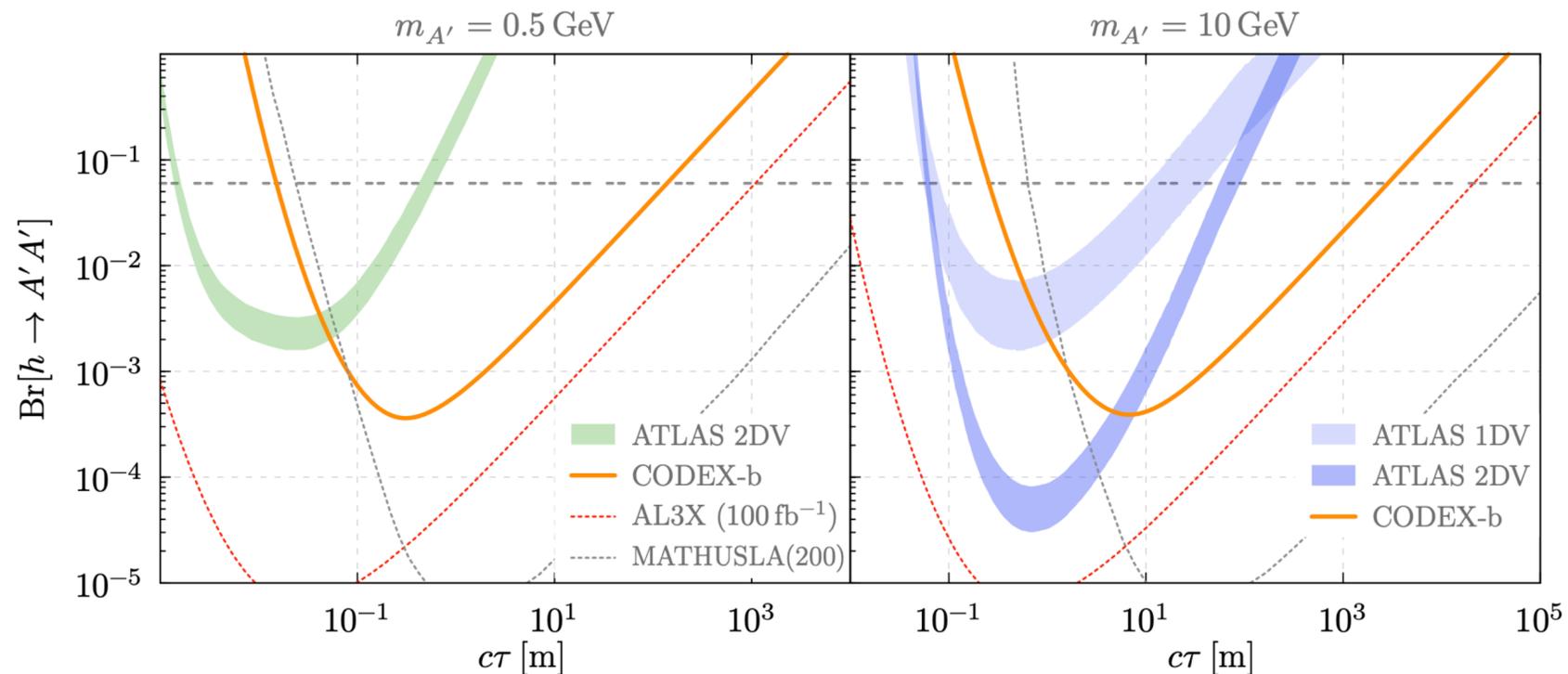
**MATHUSLA @ CMS = MATHUSLA200!**

Showing sensitivity for  $Br(h \rightarrow \text{LLP})$ .

Comparing MATHUSLA and CODEX-b.

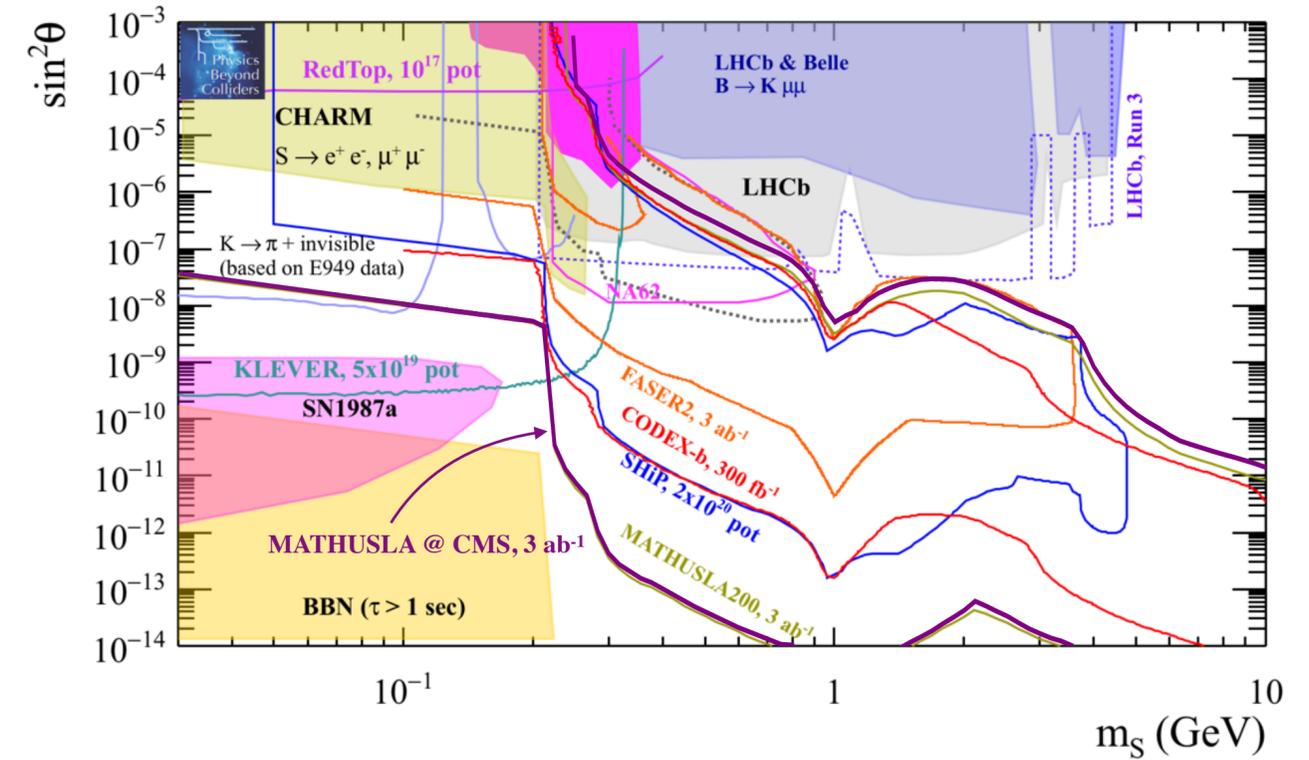
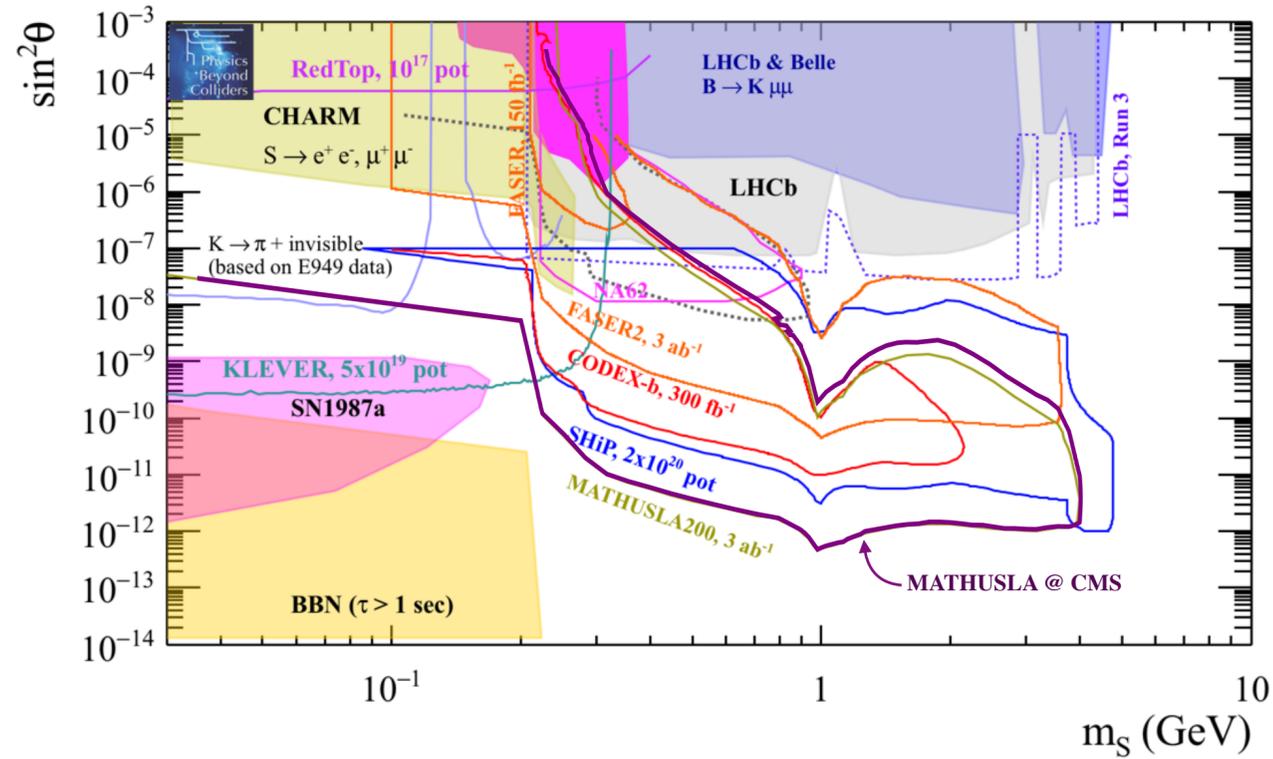
Familiar result: orders of magnitude improvement over main detector possible, especially for hadronically decaying or light LLPs.

ANUBIS sensitivity almost identical to MATHUSLA, if backgrounds can be controlled.



MATHUSLA update 2009.01693  
 CODEX-b EOI 1911.00481  
 Hirsch, Wang 2001.04750

# LLP Sensitivity: SM+S

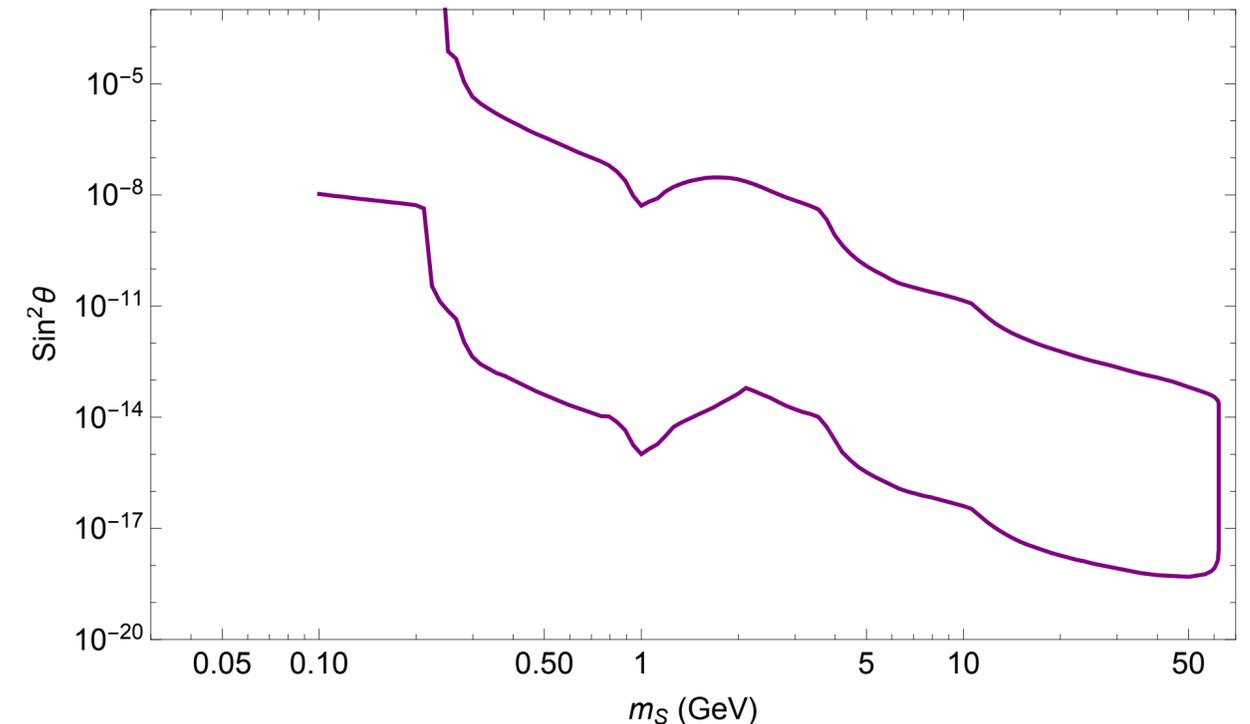


LLP production in exotic meson decays.  
Results from PBC report 1901.09966 ~ unchanged.

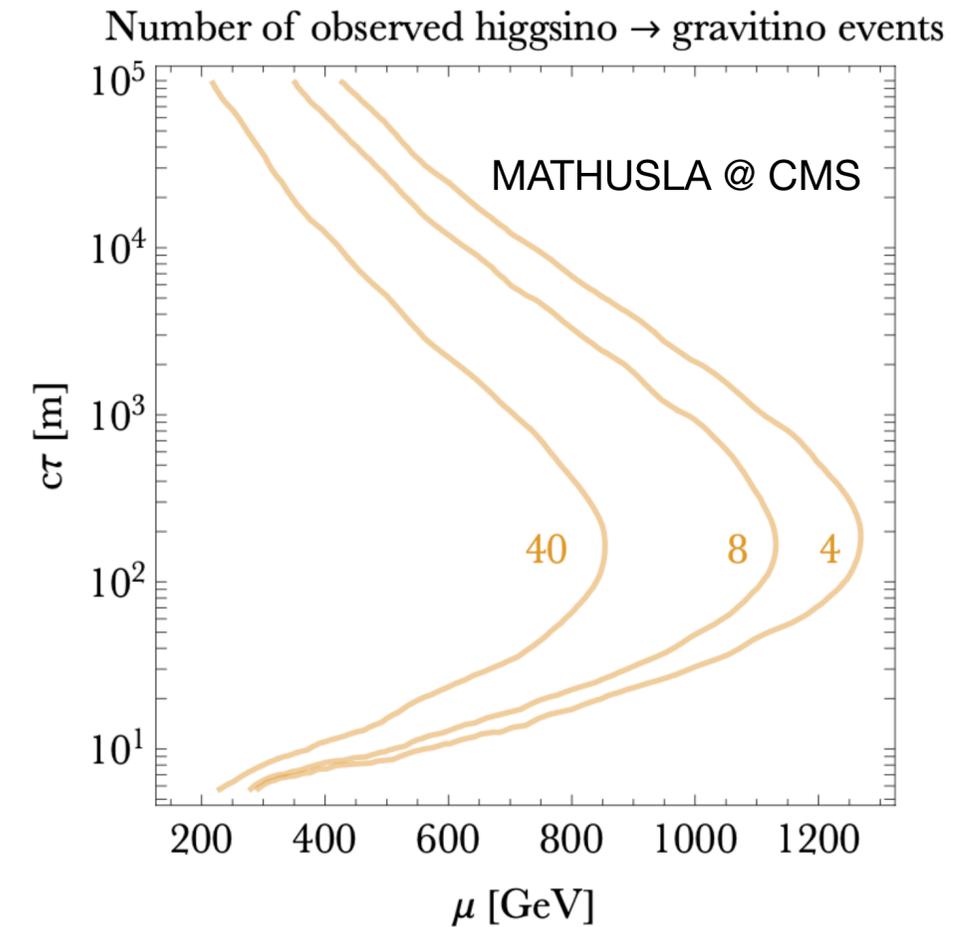
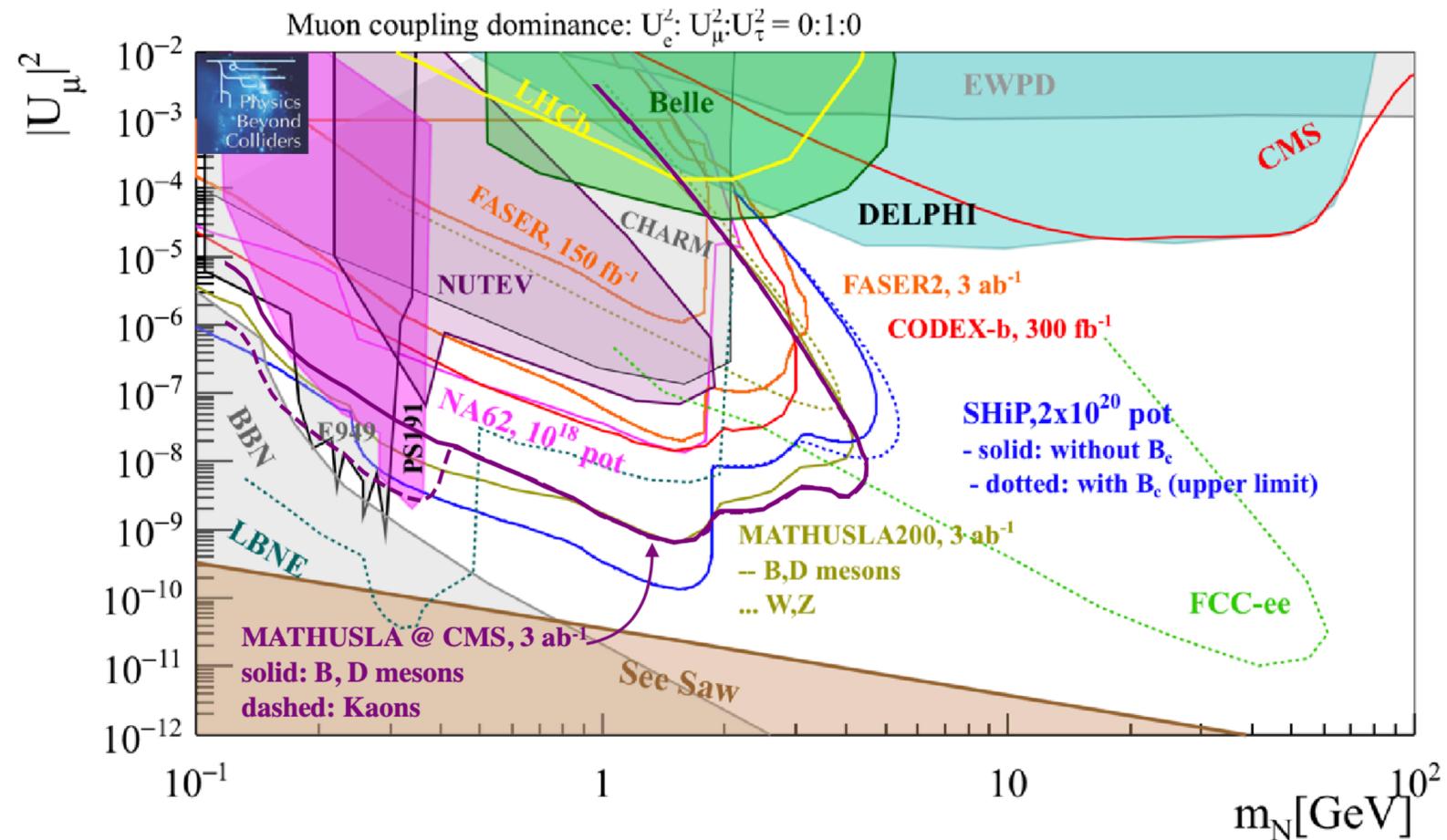
**FASER + CODEX-b + MATHUSLA allows LHC to cover parameter space very nicely.**

**Huge** sensitivity boost if LLPs are produced in exotic higgs decays (1% on right) as well: **the LHC advantage!**

Note these sensitivity estimates do not take reconstruction efficiency in the detector into account. Topic of ongoing study!

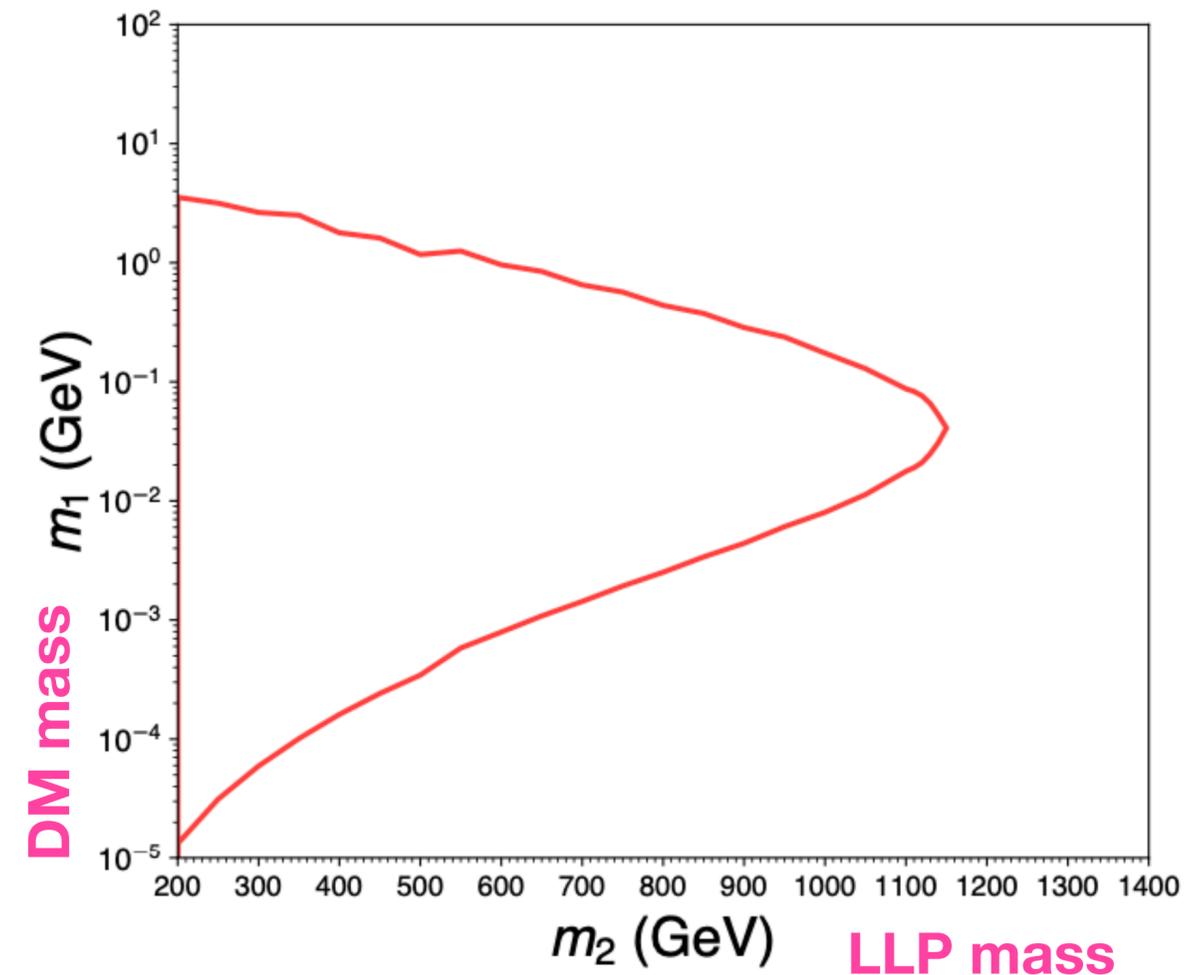
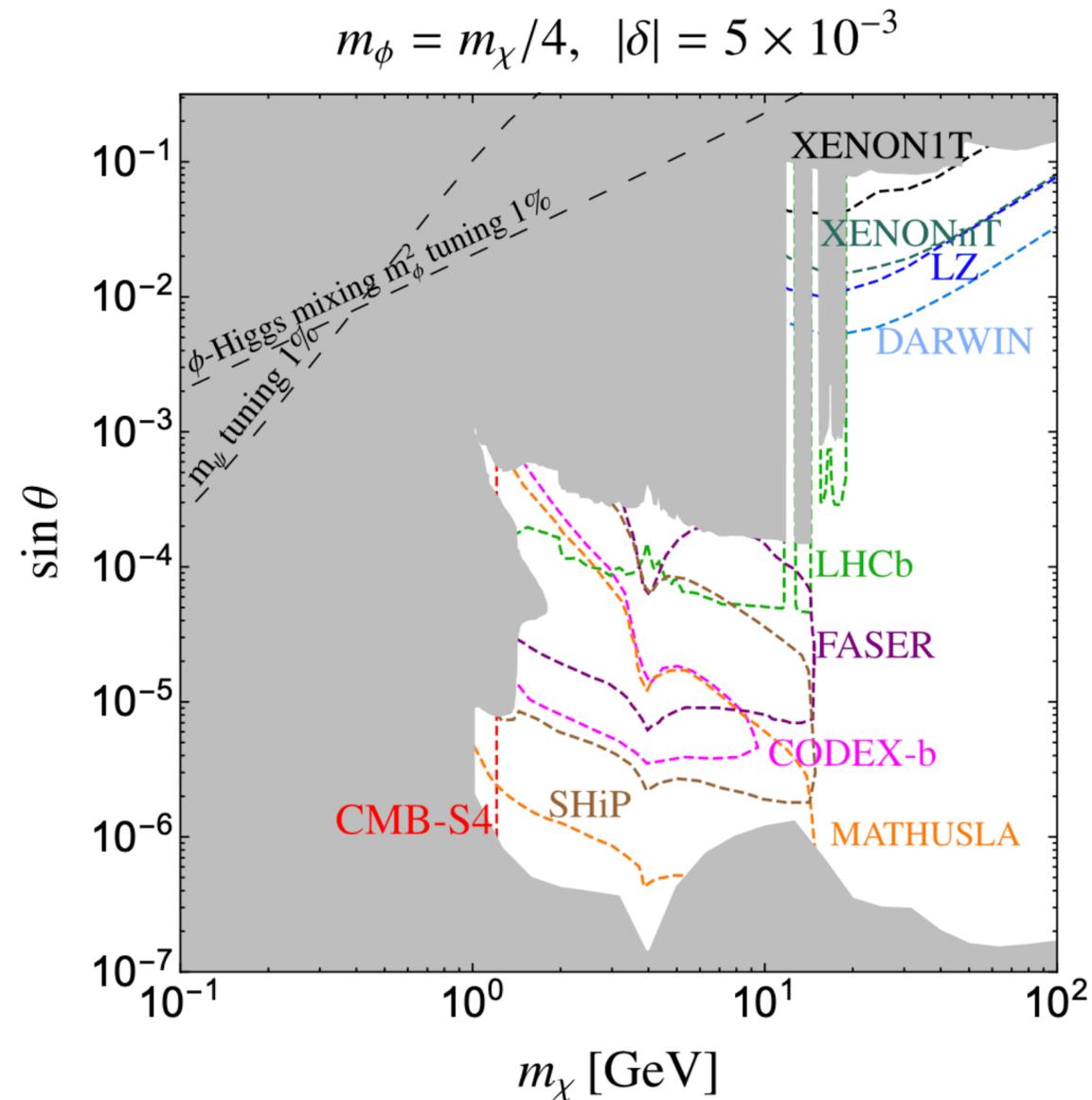


# LLP Sensitivity: RHN and Higgsinos



# LLP searches = DM searches!

In many DM scenarios, properties of LLP in primordial plasma control DM abundance. LLP searches can be best or **ONLY** way to discover DM!



inelastic DM model (1810.01879, Berlin, Kling) can be discovered via **SM+S LLP searches** at much lower mixing angles than direct detection experiment!

**MATHUSLA @ CMS reach for Freeze-In DM** (1908.11387, No, Tunney, Zaldivar).

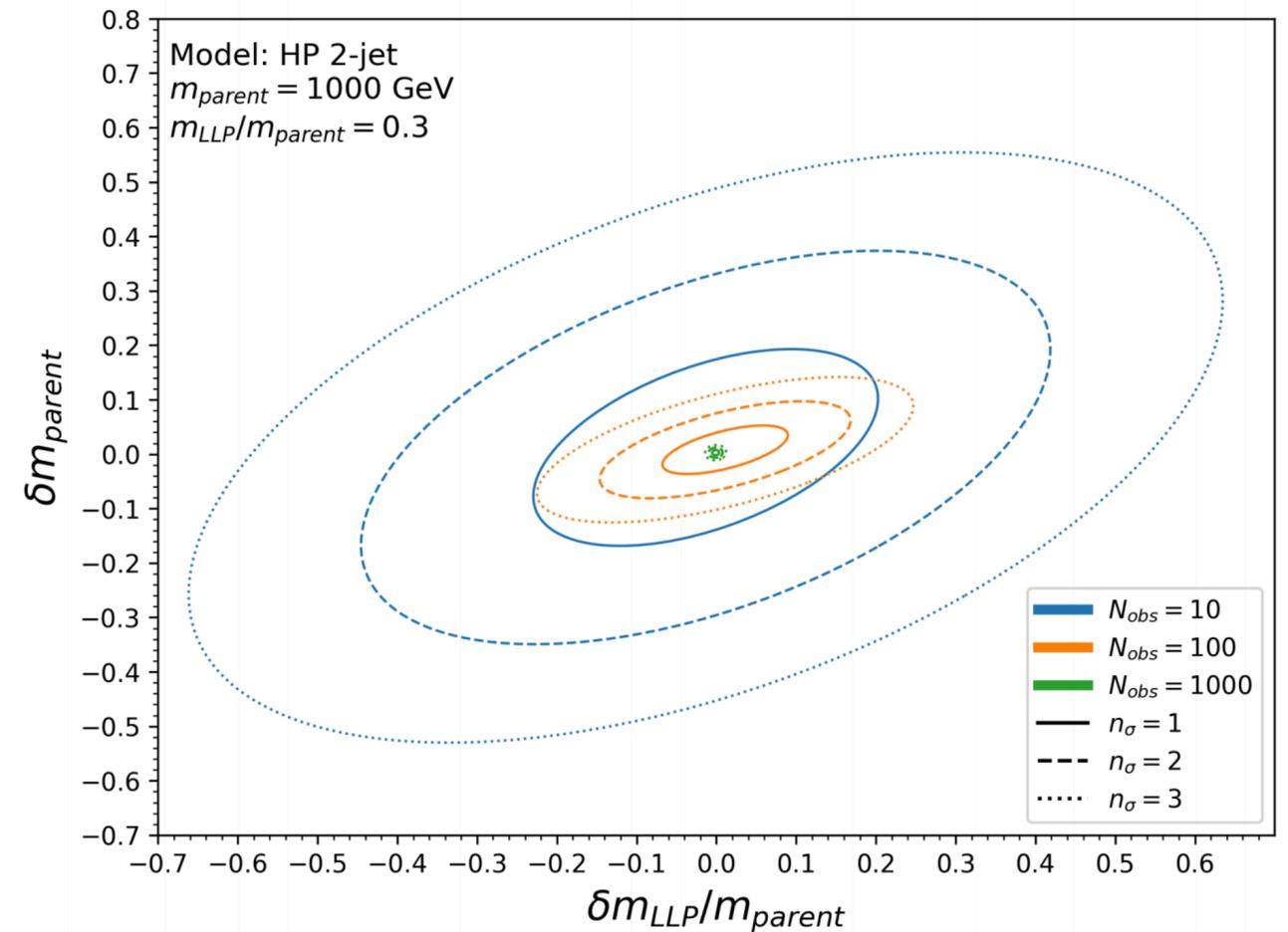
# CMS Integration: Characterizing the new Physics

MATHUSLA can supply L1 trigger signal to CMS → record main detector information on LLP production event!

Geometrical information in MATHUSLA gives info on **LLP boost, decay mode, invisible decay component.**

Analysis with main detector information reveals **production mode** and parameters of underlying model (**parent mass, LLP mass**) with ~ **100 observed events!**

1705.06327 DC, Peskin  
1809.01683, Ibarra, Molinaro, Vogl



2007.05538, Jared Barron, DC



# Backgrounds at MATHUSLA: Cosmics

Test stand measurements confirmed expected downward cosmic ray flux.

$$N_{\text{down}} \sim 3 \times 10^{14}$$

Does not constitute LLP background. However, **cosmic rays hitting the floor** can produce **upwards traveling particles**, mostly  $e^{\pm}$ ,  $p$ ,  $n$ :

$$N_{\text{up}} \sim 2 \times 10^{10}$$

Random crossings unlikely to produce fake LLP DVs ( $\ll 0.01$ ), but **tiny fraction of upwards traveling particles can produce fake DV via decay to three charged tracks.**

Might get  $O(10)$  from pions and muons. Rare production of  $K_L^0$  harder to estimate. Veto strategies are available. Working on precise estimates & studying rejection.

# Backgrounds at MATHUSLA: LHC Muons

Refined earlier estimates of muon flux with more precise GEANT4 modelling of rock layers between CMS and MATHUSLA, CMS detector, and CMS cavern.

Upward muon rate is **higher** than earlier MATHUSLA200 estimates due to less shielding from LHC collision. Over HL-LHC run:

$$N_{\mu} \approx 2 \times 10^8$$

Not an LLP background, but can get  $O(10) \mu \rightarrow eee\nu\nu$  decays. Several vetoes available (floor detector, main detector, ...).

# Backgrounds at MATHUSLA: Atmospheric $\nu$

First full simulation study (GENIE 2.12.10) of background from inelastic scattering of atmospheric neutrinos off nuclei in the air-filled decay volume.

Using measured atmospheric neutrino flux by Frejus, get  $\sim 30$  “fake” DVs per year of running, reduced to  $< 1$  by imposing “slow proton veto” thanks to good timing resolution of tracker.

Neutrino flux from HL-LHC is dominated by secondary production from decaying mesons in CMS HCAL.  $\ll 1$  events per year.

These results are lower than previous estimates. Neutrino background unlikely to be a problem for MATHUSLA LLP searches!

# Conclusions

External LLP detectors for the LHC can probe deep into LLP parameter space, for both scalar-portal-FIPs and general LLPs.

**DM search program is not complete without LLP searches!**

**Significant recent progress for MATHUSLA collaboration.** New results focus effort on outstanding issues, **new member contributions welcome:**

- R&D for tracker hardware: extruded scintillators, fibers, SiPMs, trigger, DAQ
- simulation studies of rare backgrounds, especially  $K_L^0$  production from CRs hitting the floor
- LLP reconstruction efficiency for light, low-multiplicity LLPs.
- → geometry optimization
- Cosmic ray physics case (first study to appear shortly, investigating benefit of installing hybrid analog-digital RPC layer in roof for CR science program)
- Produce TDR by 2021, prototype module few years after that, then full detector for HL-LHC.